

## SECULAR EVOLUTION OF SPIRAL GALAXIES

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## ABSTRACT

It is now a well established fact that galaxies undergo significant morphological transformation during their lifetimes, manifesting as an evolution along the Hubble sequence from the late to the early Hubble types. The physical processes commonly believed to be responsible for this observed evolution trend, i.e. the major and minor mergers, as well as gas accretion under a barred potential, though demonstrated applicability to selected types of galaxies, on the whole have failed to reproduce the most important statistical and internal properties of galaxies. The secular evolution mechanism reviewed in this paper has the potential to overcome most of the known difficulties of the existing theories to provide a natural and coherent explanation of the properties of present day as well as high-redshift galaxies.

*Key words* : galaxies: structure — galaxies: dynamics — galaxies: evolution

## I. INTRODUCTION

It is a generally accepted view that our understanding of the mechanisms and processes responsible for the formation and evolution of galaxies is incomplete. However, the degree of this incompleteness does not come into sharp focus until we assemble our most comprehensive and up-to-date observational knowledge, both on the large-scale distribution as well as on the internal properties of galaxies, and compare these with the predictions of our working theoretical models to try to make a coherent picture.

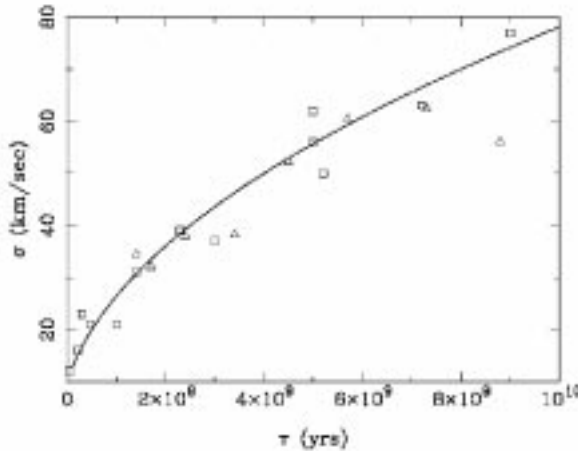
Take our own home galaxy, the Milky Way, as an example. It is a typical field galaxy of Sbc type (de Vaucouleurs & Pence 1978) in a small group environment. Existing theories offer several possible ways for the formation of this type of galaxy. The scenario offered by the earliest monolithic collapse model (Eggen, Lynden-Bell, & Sandage 1962) is that the Galaxy's mass distribution acquired most of its shape from the very beginning, i.e. about a Hubble time ago, and subsequently underwent only passive luminosity evolution driven by star formation, nucleosynthesis and element recycling. One problem with this static picture is that the observed kinematics of the different age groups of stars in the Milky Way disk differ systematically, manifesting as the well-known age-velocity dispersion relation of the solar neighborhood stars (Wielen 1977). In the primordial collapse model, there is nothing which could account for this secular increase of the velocity dispersion of disk stars.

Recent deep surveys have found that galaxies in the general field environment similar to that occupied by the Milky Way have undergone significant morphological transformation over the cosmic time, following a similar trend though not to as dramatic a degree as the cluster galaxies we will discuss next. It is found that more field galaxies are of earlier Hubble types in

the nearby universe than at the higher redshifts (Lilly et al. 1998). There is also a population of so-called faint-blue galaxies, which are in fact  $L_*$  galaxies having luminosities and sizes similar to the Milky Way, which exist at the intermediate redshifts but which have all but disappeared in the nearby universe (Ellis 1997).

Could this observed morphological evolution be due to the hypothesized major/minor merger events? The thinness of the Milky Way disk, the lack of a large population of counter rotating stars, as well as the smoothness of the age-velocity dispersion relation (Figure 1) all argue against either a major merger or the accretion of a satellite of significant mass over the past Hubble time (Ostriker 1990; Wyse 2001). There is indeed a known discontinuity in the Galaxy age-velocity dispersion relation at about 11 Gyr ago (Binney, Dehnen, & Bertelli 2000; Gilmore, Wyse, & Norris 2002). Although a merger has been proposed as its origin, the emergence of the spiral structure on the disk at about the same time seems a more likely cause for this discontinuity and for the creation of the thick disk. Furthermore, the Milky Way bulge stellar populations are distinctively different from its known satellites such as the Magellanic clouds (Gilmore 2001), further arguing against the building of a significant fraction of the Bulge through satellite accretion.

Is the bar-driven gas accretion process (Kormendy 1982, 1993; Pfenniger & Norman 1990; Combes et al. 1990; Pfenniger & Friedli 1991; Friedli & Benz 1993; Norman, Sellwood & Hasan 1996; Courteau, de Jong & Broeils 1996) responsible for Bulge building? It was indeed shown in numerical simulations that gas accretes towards the center after being shocked crossing the galactic bar potential; however, the abundance analyses of stars in the thick disk and bulge of the Milky Way indicate a high  $[\alpha/\text{Fe}]$  ratio (Gilmore 2001), where  $\alpha$  elements O and Mg are created primarily in type II su-



**Fig. 1.**— The age-velocity dispersion relation of the solar neighborhood stars. Points: observational data [squares: Wielen (1977); triangles: Carlberg et al. (1985)]. Curve: fitted disk star heating due to spiral structure (Zhang 1999).

pernovae from massive young stars and the Fe is generated in type I supernovae from lower-mass stars of much greater ages. The high  $[\alpha/\text{Fe}]$  abundance ratio can arise if the Bulge and thick-disk stars all formed within a short time, thereby suppressing enrichment in Fe which requires longer timescales. These timescale considerations suggest that most of the Bulge stars have formed very early on and probably not far from their present locations. This limits the importance of gaseous inflow in building the Bulge, as continuous inflows would extend the star-forming epoch and so enable Fe enrichment from the type I supernovae (B. Waller 2001, private communication; Jablonka, Gorgas & Goudfrooij 2002).

We now turn our attention to dense clusters. This is in fact the environment where the morphological transformation of galaxies was first indicated through the so-called Butcher-Oemler (BO) effect (Butcher & Oemler 1978a,b). When it was discovered, the BO effect referred to a bluing of colors for galaxies in the dense clusters at the intermediate redshifts compared to similar density clusters in the local universe, which contain mostly red early type galaxies. Recent HST observations (Couch et al. 1994; Dressler et al. 1994) have been able to resolve the morphology of the BO galaxies and show that they are mostly late type disks; therefore the BO effect is now considered not only a color evolution effect but also a morphological transformation effect. Major mergers are not likely to be responsible for the observed morphological transformation of the Butcher-Oemler (BO) cluster galaxies, due to the high-speed nature of the encounters (Dressler et al. 1997), as well as the finding through numerical simulations that dissipationless mergers between preexisting stellar disks cannot account for the kinematics of the early

type galaxies, especially the large ratio of the rotational to random velocities (Heyl, Hernquist, & Spergel 1996; Cretton et al. 2001); whereas the spiral disks in BO clusters are found to have formed most of their stars before the observed morphological transformation had taken place (Franx & van Dokkum 2001). Minor mergers are also unlikely to be the main driver because there does not seem to be a large reservoir of dwarf spheroidal satellites in these clusters (Trentham 1997) to cause the simultaneous morphological transformation of the large number of BO galaxies.

The rapid morphological changes of galaxies in clusters are also not likely to be produced by a ram pressure gas-stripping mechanism alone (Gunn & Gott 1972), since stripping could not lead to a change of bulge-to-disk ratio (Sandage 1983), whereas the morphological transformation of the BO galaxies from the late type disks to S0s and ellipticals requires such a change. The so-called “harassment” mechanism had been shown to be effective in stripping away the outer gas and transforming the small late-type disks into early type dwarf galaxies (Moore et al. 1996), yet it was shown to be much less effective on large disks (Gnedin 1999).

Thus we see, for both the field and cluster galaxies, the existing theories are unable to provide satisfactory explanations of their formation and evolution.

## II. SECULAR MORPHOLOGICAL EVOLUTION OF GALAXIES

During the past few years, a new mechanism for the secular evolution of galaxies has been proposed (Zhang 1996, 1998, 1999) which operates through large scale coherent patterns in galaxies such as spirals, bars or other skewed mass distributions. This mechanism has been overlooked by past workers in this field due to some subtle features of its operation.

### (a) The Source and Sink of Outward Angular Momentum Transport

Three decades have past since the publication of Lynden-Bell & Kalnajs’ seminal paper (Lynden-Bell & Kalnajs 1972, hereafter LBK) demonstrating that spiral density waves in disk galaxies can transport angular momentum (as well as energy) outward. Associated with this outward angular momentum transport is an expected secular redistribution of disk matter, coinciding with the trend of the entropy evolution of a self-gravitating system; i.e., towards a more and more centrally concentrated core together with the build-up of an extended outer envelope. However, this latter aspect has rarely been discussed, if at all, in the context of the LBK theory since the publication of their paper. One of the reasons for this disparity is the equally well-known second result from the same paper: there is no interaction between a steady amplitude spiral density wave and the basic state (i.e. the axisymmetric part) of the galactic disk except at the inner and outer

Lindblad resonances (ILR and OLR). There is thus an apparent lack of consistency in the LBK theory since it is difficult to imagine a spiral wave constantly transporting angular momentum outward without the basic state mass distribution undergoing a corresponding change. One possible way out of the apparent contradiction is if the spiral pattern is a transient phenomenon as was assumed by LBK. The outward angular momentum transport then leads to a temporary and short-lived growth of a wave train between the ILR and OLR: since the wave has negative angular momentum density inside corotation relative to the axisymmetric disk, the outward angular momentum transport leads to its own spontaneous growth.

However, studies of grand design galaxies in groups (Elmegreen & Elmegreen 1983, 1989) suggest that most spiral patterns last for at least 10 revolutions if they are triggered by interactions. Recent N-body simulations have also produced long-lived spiral patterns in isolated stellar disks which lasted more than 10 revolutions with essentially constant pattern speed and wave amplitude (Figure 2).

Such long-lived spiral patterns are related to the spontaneously growing *modes* in the galactic resonant cavity rather than *wave trains*. Furthermore, the spiral modes cannot grow indefinitely. The wave amplitude has to be clamped at a finite value as is observed in real galaxies. The two conditions, i.e., the continuous outward angular momentum transport by a long-lived spiral pattern coupled with a finite wave amplitude, imply that at the quasi-steady state of the wave mode the outward-transported angular momentum cannot come from the wave itself (for otherwise the wave amplitude will continue growing without bound), but has to come from the basic state of the galactic disk, since the wave and the basic state are the only two subsystems that we divide the disk into. The secular evolution of the mass distribution of the galactic disk is thus an inevitable consequence of the requirement of global angular momentum conservation and the assumption of a quasi-stationary spiral structure; or, to put it in another way, the globally self-consistent quasi-steady spiral solution is maintained at the expense of a continuous secular basic state evolution. The source and sink of the angular momentum transported by a quasi-stationary spiral mode both reside in the basic state: they are the inner and outer disk, respectively (the dividing line between the loading and unloading of the angular momentum is at the corotation radius, as we will discuss below). The energy and angular momentum exchange between the wave and the basic state thus serves as a damping mechanism for the spontaneously growing density wave mode: since the wave has negative energy and angular momentum density inside corotation, to receive energy and angular momentum from the basic state in the inner disk limits the wave growth; similarly, since the wave has positive energy and angular momentum density outside corotation, to dump energy and angular momentum to the basic state also limit the wave

growth in the outer disk. In the end the nonlinearity in this exchange process helps to clamp the wave amplitude at a particular value which is mainly determined by the basic state properties (Zhang 1998).

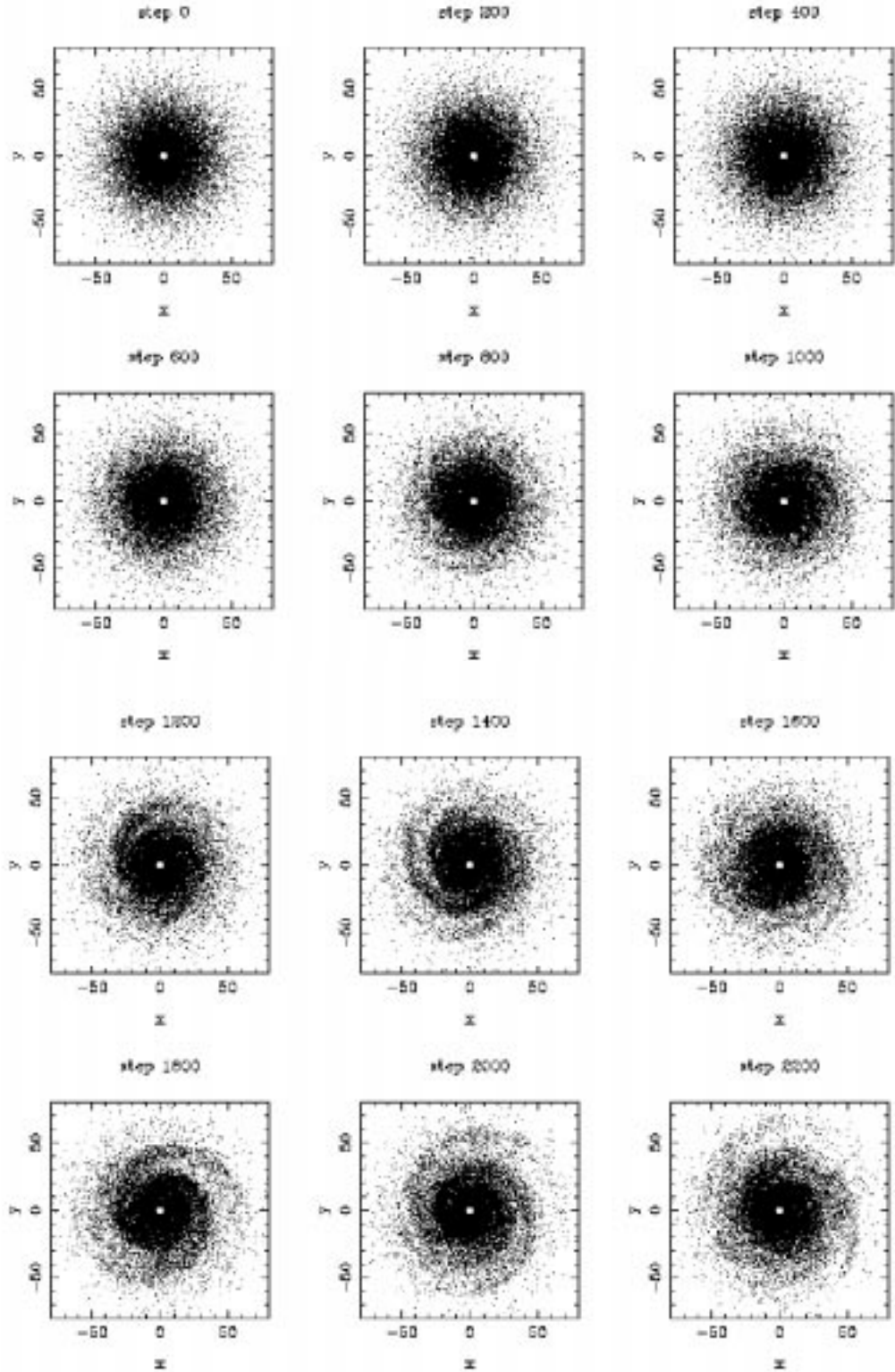
What then is the mechanism through which the outward-transported energy and angular momentum are loaded onto the density wave in the inner disk, as well as unloaded in the outer disk? The relevant mechanism obviously has to involve the interaction of the basic state and the wave mode: Specifically, it has to involve a dissipative energy and angular momentum exchange between the wave and the basic state; i.e., the loading of angular momentum onto the wave from the basic state inside corotation, and unloading of this angular momentum outside corotation, with the wave itself being the carrier for the angular momentum transport. Such a mechanism for wave/basic state interaction was indeed found (Zhang 1996, 1998, 1999), and we summarize the essential characteristics of this mechanism below.

It was first shown in Zhang (1996) that for a self-sustained spiral mode, the minimum of the gravitational potential of a spiral density wave lags behind the maximum in density in the azimuthal direction inside corotation, and vice versa outside corotation. The phase shift between the potential and density spirals means that there is a torque exerted by the potential spiral on the density spiral, and, at the quasi-steady state of the wave mode, a secular transfer of energy and angular momentum between the disk matter and the density wave. The existence of the phase shift between the potential and density spirals of a self-sustained spiral mode is partly a result of the long range nature of gravitational interaction. It is for this reason that a skewed bar or other skewed large scale patterns will also possess a phase shift and the associated collective dissipation through essentially the same mechanism.

The torque  $T(r)$  applied by the spiral potential on the disk density in an annulus of unit width can be written as (Zhang 1996, 1998)

$$T(r) = dL/dt = r \int_0^{2\pi} -\Sigma(r \times \nabla \mathcal{V})_z d\phi \\ = -\pi m r \Sigma_1(r) \mathcal{V}_1(r) \cdot \sin(m\phi_0(r)), \quad (1)$$

where  $\Sigma$ ,  $\mathcal{V}$ ,  $\Sigma_1$ ,  $\mathcal{V}_1$  are the disk surface density, potential, the spiral perturbation density and spiral perturbation potential in the annulus, respectively;  $L$  is the angular momentum of the disk matter in the annulus,  $\phi_0$  is the potential-density phase shift, which is found to be positive inside corotation (potential lags density) and negative outside corotation (potential leads density), and  $m$  is the number of spiral arms. It can be seen from (1) that the torque  $T(r)$  is non-zero only when the phase shift  $\phi_0$  is non-zero. Furthermore, the contributions of both the gravitational and advective torque couplings are included in the single torque integral given in equation (1) at the quasi-steady state of



**Fig. 2.**— Morphological evolution of an N-body spiral mode in a purely stellar disk. Between the adjacent frames the pattern rotates about  $120^\circ$ . From Zhang (1998).

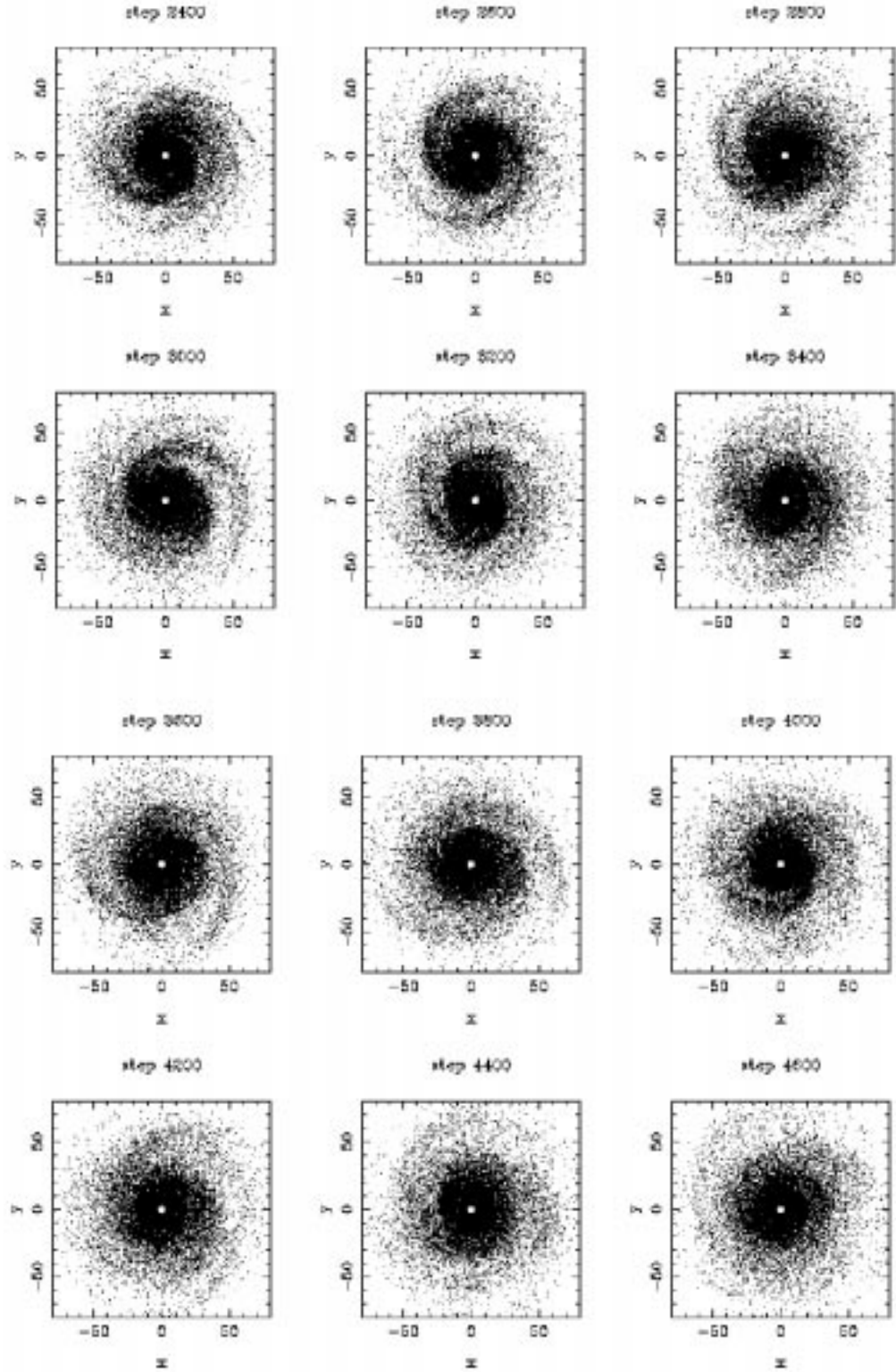
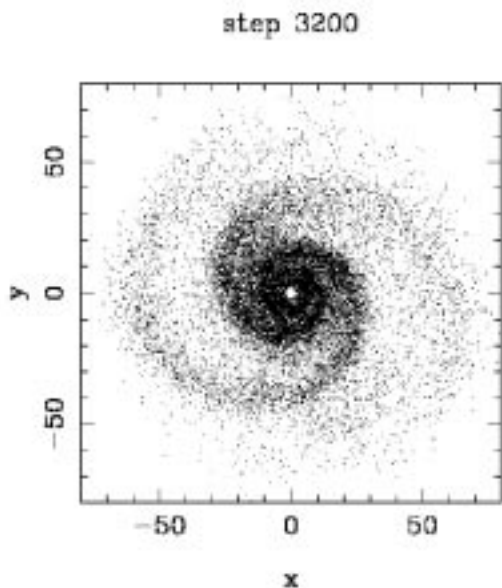


Fig. 2.— (continued).

the wave mode. The proof of this fact is given in the Appendices of Zhang (1998,1999).

The energy and angular momentum exchange between the disk matter and the density wave at the quasi-steady state as indicated by equation (1) is achieved through a temporary local gravitational instability at the spiral arms (Zhang 1996). The length scale of this instability at the solar radius is calculated to be about 1 kpc, comparable to the length scale of the giant HI and molecular complexes near the Galactic spiral arm region (Elmegreen 1979).

In Figure 3, we show an image of an N-body spiral mode from Zhang (1996). There we see the density enhancement at the inner edge of the spiral pattern inside corotation (the corotation radius  $r_{co} = 30$  in this case), reminiscent of the dust lanes observed at the leading edges of the spiral arms of physical galaxies which signal the presense of gaseous shocks. However, here in a collisionless particle disk of the N-body simulation we have obtained the signature of a shock wave, which is a phenomenon generally attributed to a dissipative system. In what follows we present further evidence that a spiral density wave is in fact a propagating front of collisionless shock (Zhang 1996).



**Fig. 3.**— Detailed morphology of a spontaneously-formed N-body spiral mode, showing the density maxima at the leading edge of the spiral pattern for locations inside corotation (Zhang 1996).

In Figure 4, the azimuthal variations of the different disk parameters are plotted. We see from (a) that the potential indeed lags the density for this typical radial location inside corotation. Furthermore, from (c) it is

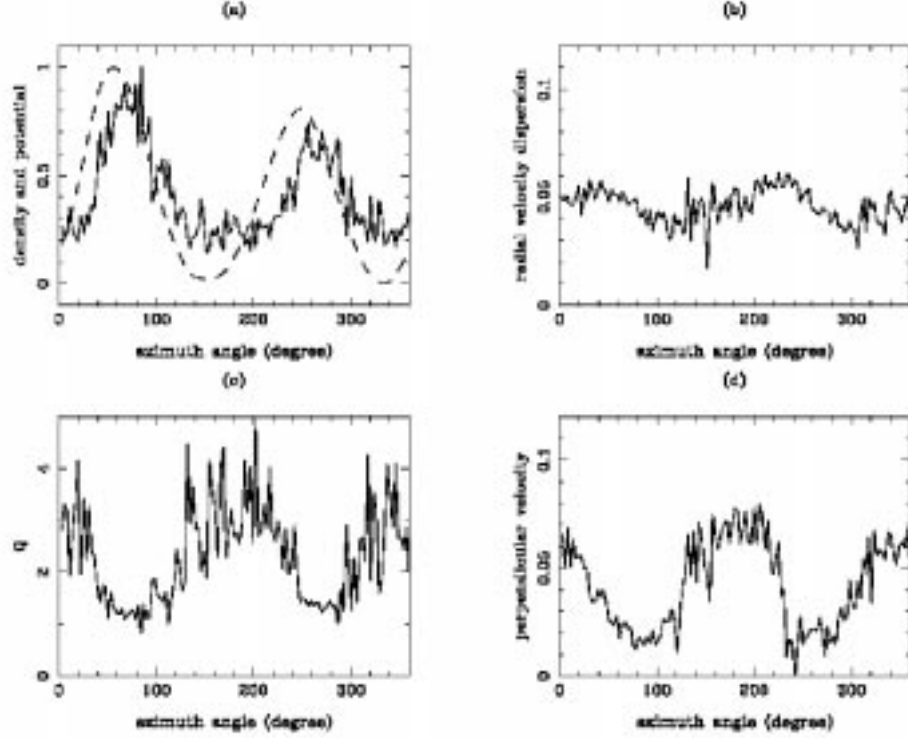
seen that Toomre’s  $Q$  parameter has a clear minimum in the higher density region of the spiral arms. This sudden drop in  $Q$  signals the presence of local gravitational instability at the arm region. (d) shows that the velocity component perpendicular to the spiral arm suffers a sharp jump from supersonic to subsonic (the average sound velocity is about 0.04, as shown in (b)), further reinforcing the impression of the presence of a shock.

The gravitational instability and the associated small-angle scattering of the streaming stars at the arms of a self-sustained spiral wave is what breaks the conservation of the Jacobi for a single stellar orbit in a smooth and steady-amplitude spiral potential, or equivalently the no-wave-basic-state interaction conclusion of LBK, and this allows the stellar orbit to display secular decay or increase.

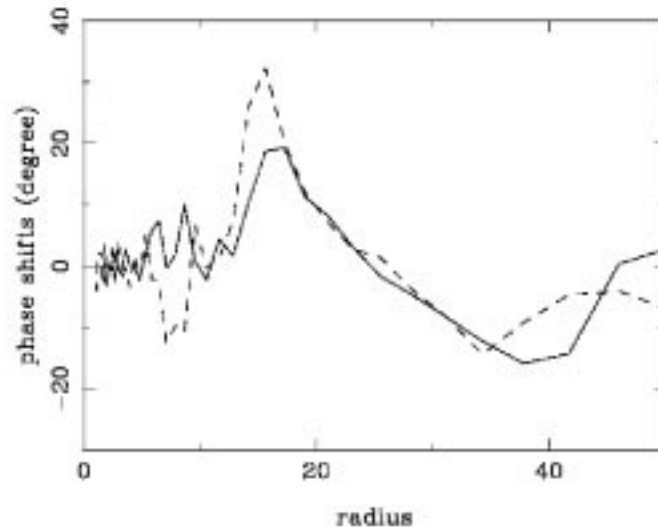
Essentially the same result can be obtained for a star-gas two-component disk (Zhang 1998). In the past, discussions of secular evolution in galaxies have focused on the accretion of gas under the influence of a central bar. This originates partly from the mis-conception that “gas is dissipative, whereas stars are not”. However, as is well known, the microscopic viscosity in the gas component is inadequate to support a reasonable accretion rate even for proto-stellar accretion disks (see, e.g. Pringle 1981). Instead, the gravitational viscosity due to the collective dissipation effect of the non-axisymmetric large-scale structures has to be responsible even for the accretion of the gas component. This is because gravity does really distinguish whether the underlying matter is made of stars or gas. The past star-gas two-component N-body simulations have often found that the phase shift between the stellar and gaseous densities are usually small (Carlberg & Freedman 1985), especially in comparison with the phase-shifts of these densities with respect to their common spiral potential (Figure 5). These phaseshifts causes stars and gas to both drift towards the center as well as being heated. We will calculate these spiral induced evolution rates quantitatively in the next subsection.

### (b) Astrophysical Consequences

As a result of the wave-basic state angular momentum exchange, an average orbiting star in the basic state inside corotation loses energy and angular momentum to the wave secularly and tends to spiral inward (Figure 6). Similarly, a star outside corotation gains energy and angular momentum from the wave and drifts outward secularly (Figure 7). The mean orbital radius evolution leads to a corresponding disk surface density evolution which we plot in Figure 8, where the dashed line in each frame indicates the surface density at the earlier time step, and the solid line the later time step. Since the star inside corotation drifts inward, and outside corotation drifts outward, at corotation the surface density decreases with time. Note that as a galaxy evolves, the spiral pattern speed tends to

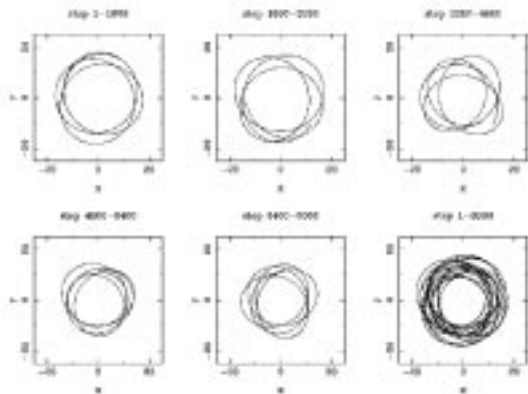


**Fig. 4.**— Spiral gravitational shock. Different frames show the azimuthal distributions of the following parameters: (a) Surface density (solid line) and negative potential (dashed line). (b) Radial velocity dispersion. (c) Toomre's  $Q$  parameter. (d) Velocity component perpendicular to the spiral arm. The above quantities are computed at a radius of 14.5 (From Zhang 1996).

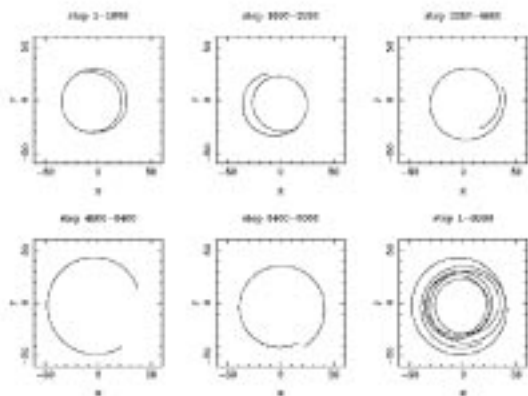


**Fig. 5.**— Potential and density phase shift for the stellar component (solid) and the gas component (dash), respectively, for the spiral mode in the two-component N-body simulations of Zhang (1998) at time step 1600.

decrease and thus the corotation radius tends to move outward (Toomre 1981). We also see the trend of increasing disk central density together with the build-up of the extended outer envelope, as predicted.



**Fig. 6.**— Evolution of orbit trajectory for a typical star inside corotation. From Zhang (1996).



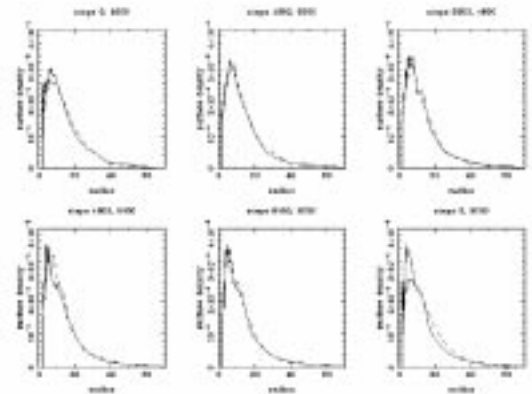
**Fig. 7.**— Evolution of orbit trajectory for a typical star outside corotation. From Zhang (1996)

A quantitative estimate of the rate of orbital change can be obtained from equation (1), which turns out to be (Zhang 1998)

$$\frac{dr}{dt} = -\frac{1}{2}F^2v_0 \tan(i) \sin(m\phi_0), \quad (2)$$

where  $F$  is the fractional wave amplitude,  $v_0$  is the circular velocity of the star,  $i$  is the pitch angle of the spiral, and  $m$  and  $\phi_0$  are again the number of spiral arms and the potential-density phase shift, respectively.

To calculate the secular evolution rate for our own Galaxy, we assume a two-armed spiral pattern of 20%



**Fig. 8.**— Evolution of disk surface density. From Zhang (1996).

amplitude and  $20^\circ$  pitch angle (Drimmel 1991), which is appropriate for the average Hubble type that our Galaxy had during the past  $10^{10}$  years of evolution. This set of values gives an orbital decay rate of 2 kpc per Hubble time using (2); the same set of spiral parameters also nicely fitted the observed age-velocity dispersion curve (Figure 1) using the velocity diffusion equation we will derive later, increasing the credibility of this particular set of choice of spiral parameters.

Therefore, a star in the Sun's orbit will not make it all the way in to the inner Galaxy in a Hubble time. However, the corresponding mass accretion rate across any Galactic radius inside corotation is given by

$$\frac{dM}{dt} = 2\pi r \frac{dr}{dt} \Sigma, \quad (3)$$

where  $\Sigma$  is the disk surface density. Using (3), and a solar neighborhood average disk surface density of  $60 M_\odot \text{pc}^{-2}$  (Bahcall 1984; Kuijken & Gilmore 1989), the mass accretion rate for the Galaxy disk is found to be about  $6 \times 10^9 M_\odot$  per  $10^{10}$  yr. A substantial fraction of the Galactic bulge can thus be built up in a Hubble time. The vertical drift (or velocity dispersion increase) needed for a star to truly become a bulge star is produced by the isotropic heating effect accompanying accretion, which we will discuss a little later.

Observationally, bulges are found to be old, and encompass a wide range of metallicities (see, e.g. Goud-frooij, Gorgas & Jablonka 1999), with a clear radial gradient in both the age and metallicity distribution which appears to be the continuation of a similar gradient in the disk (Courteau et al. 1996). The secular evolution process discussed in this work predicts that the abundance gradient will be enhanced with time, since it is effectively an inner disk contraction process which amounts to about 2 kpc of disk scalelength reduction in a Hubble time. This, coupled with the shorter dynamical time scale in the inner disk and the resulting



enhanced element recycling rate, leads to an increase of the abundance gradient with time. This is in contrast with the gaseous-bar secular evolution scenario (e.g. Friedli, Benz & Kennicutt 1994 and the references therein) which generally predicts a flattening of the abundance gradient due to gas inflow. Gas accretion also tends to create a bluing of the nuclear region even though early type bulges are often observed to be red. Furthermore, while gas accretion could be important for the morphological transformation among later Hubble types, it is insufficient to explain the transformation of Sb to Sa, and Sa to S0, etc.. Bulge formation also cannot be solely due to the dissolution of a pre-existing stellar bar as some theories suggest since observationally the bulge light is found to be added onto the disk light, instead of substrated from it (Wyse, Gilmore, & Franx 1997). Part of the reasons previous secular evolution theories arrived at the above results was due to the unequal treatment of stars and gas, i.e. the relevant numerical simulations usually considered the *response* of the gas under the *applied* stellar bar potential; the viscosity of the gas in these calculations were also introduced artificially and its value somewhat arbitrarily.

Another important consequence of spiral-induced wave-basic state interaction is the secular heating of the disk stars, believed to be the main process responsible for producing the age-velocity dispersion relation of the solar neighborhood stars (Figure 1). As we have mentioned above, the secular heating process allows the stars to gradually drift out of the galactic plane as they spiral inward, and eventually become bulge stars.

The secular heating of the disk stars works as follows. Since a spiral density wave can only gain energy and angular momentum in proportion to  $\Omega_p$ , the pattern speed of the wave, and a disk star which moves on a nearly circular orbit loses its orbital energy and angular momentum in proportion to  $\Omega$ , the circular speed of the star, an average star cannot lose the orbital energy entirely to the wave; thus, the excess energy serves to heat the star when it crosses the spiral arm. For our Galaxy, the diffusion coefficient due to the spiral-induced secular heating is estimated to be

$$D = (\Omega - \Omega_p) F^2 v_c^2 \tan(i) \sin(m\phi_0) \approx 6.0 (kms^{-1})^2 yr^{-1}, \quad (4)$$

if using the same set of spiral parameters as used above for estimating Bulge building (i.e. a  $20^\circ$  pitch angle and 20% amplitude two armed spiral). This value of  $D$  fits very well the age-velocity dispersion relation for the solar neighborhood stars as can be seen in Figure 1. The above expression for  $D$  can be shown to be approximately independent of galactic radius (Zhang 1999), which would reproduce the observed isothermal distribution of the stellar and gaseous mass across the Galaxy (Gilmore, King & van der Kruit 1990). Since the spiral gravitational instability which mediates the wave-star energy and angular momentum exchange is a local instability, the heating of the disk stars is ap-

proximately isotropic, and all three dimensions of the velocity dispersion increases at approximately the same rate as is observed (Wielen 1977).

The velocity dispersion of the gas in the high redshift Damped  $L_\alpha$  systems (DLAs), which are believed to be the candidate primordial disk galaxies, is found to be around 10 km/s (Wolfe 2001). This can be gradually increased to the stellar velocity dispersion of 40 km/s of the thick disk stars of the present-day Milky Way-like galaxy through the above spiral heating mechanism. The metallicity of the DLA systems are found to have evolved little between  $z=2-4$  (Prochaska, Wolfe & Gawiser 2000), consistent with the fact that the disks during this period have not formed prominent spiral patterns and thus the metal enrichment evolution is not prominent. Emergence of the spiral heats the disk immediately, as confirmed in the N-body simulations. This can be a natural explanation for the discontinuity found in the age-velocity dispersion relation of the solar neighborhood stars 11 Gyr ago.

A similar energy injection into the interstellar medium can serve as the top-level energy source to power the subsequent supersonic turbulence cascade (Zhang 2002; Zhang et al. 2001), which naturally explains the size-linewidth relation of the interstellar clouds.

We thus see that the spiral and bar-induced radial mass accretion process leads to the building up of the bulge, and causes the Hubble type of a galaxy to evolve from late to early. Such morphological transformation is observationally most pronounced in dense BO clusters, though its less pronounced counterpart in the field has also been observed (Lilly et al. 1998). The enhanced mass accretion rate for cluster galaxies is in part due to the large amplitude and open spiral patterns induced through tidal interactions of neighboring galaxies, since the effective evolution rate is proportional to wave amplitude squared and the spiral pitch angle squared (equation 2) (note that the phase shift  $\phi_0$  itself is approximately proportional to spiral pitch angle). Preliminary evidence has been found that the brightness (or amplitude) of the spiral pattern is significantly high for cluster galaxies compared to the field galaxies of the same rotation curve and size (Aragon-Salamanca et al 2002). Tidal interactions among neighboring galaxies have also been found to produce enhanced disk mass accretion and nuclear activity (Byrd et al. 1986; Zhang, Wright, & Alexander 1993). The necessity of invoking environmental effects to enhance the strength of the spiral structure does not make the process we discuss less interesting or relevant. Just as in the case of the development of a human being, even though the environmental input and nourishment are important, without an innate mechanism for development and maturation, the human growth process would not happen.

### (c) Formation of Coherent Patterns in Disk Galaxies as an Example of Non-Equilibrium Phase Transitions

It is well known that for an isolated system, the direction of entropy evolution is towards an increasing degree of macroscopic uniformity, corresponding to increasing entropy. For open systems at far-from-equilibrium conditions, however, it often happens that the usual near-equilibrium thermodynamic branch of the solution becomes unstable, and new types of highly organized spatial-temporal structures emerge spontaneously. Due to its similarity to equilibrium phase transitions, this kind of spontaneous structure formation in nonequilibrium systems has been termed “nonequilibrium phase transitions”, and the structures thus formed “dissipative structures” (Glansdorff & Prigogine 1977; Nicolis & Prigogine 1977) to emphasize the constructive role of dissipation in the maintenance of these nonequilibrium structures.

The large-scale coherent patterns formed in open and nonequilibrium systems are functional as well as architectural. One of the important functions of these “dissipative structures” is to greatly accelerate the speed of entropy evolution of these systems towards reaching thermodynamic equilibrium, or at least reducing the degree of nonequilibrium. The local highly-ordered structure (which has low entropy) maintains its constant entropy in the meta-stable state by continuously exporting the entropy it produces to its environment. As a result, the entropy of the structure plus the environment increases at a much faster rate than when the system was still on the thermodynamic branch of the solution.

The spiral (or bar) patterns of galaxies have many characteristics of a typical “dissipative structure”. First, as we have shown, a quasi-stationary spiral mode is maintained by the opposing effect of the spontaneous growth tendency and local dissipation, with a continuous flux of energy, angular momentum and entropy through the system carried by the trailing spiral wave itself. Second, it can be shown that the formation of spiral structure accelerates the speed of entropy evolution of a spiral galaxy, compared to that of a uniform disk, by several orders of magnitude (Zhang 1992). Thirdly, since a spiral mode is a global instability in the underlying basic state of the disk, the spontaneous emergence of the spiral pattern (which is obviously a global symmetry-breaking process) happens as long as the disk satisfies certain far-from-equilibrium constraints (i.e. the basic state characteristics must allow the linear growth rate of a spiral mode to be greater than zero). Lastly, the characteristics of the quasi-stationary spiral pattern formed are determined solely by the properties of the basic state, and not by the accidents of the external perturbations. This last point is reinforced by the N-body simulations of tidal spiral patterns in slightly unstable disks, where it was found that after the initial transient state, the characteris-

tics of the tidally-induced patterns correlate strongly with the properties of the basic state, rather than with the nature of the encounter (Donner & Thomasson 1994). These characteristics of the spiral structure clearly identify it as an example of a “dissipative structure” defined by Glansdorff & Prigogine (1971), and the spontaneous formation and stabilization of a large-scale spiral mode as an example of a nonequilibrium phase transition.

### III. COMPARISON OF THE HIERARCHICAL CLUSTERING AND THE SECULAR EVOLUTION PREDICTIONS

Currently the working paradigm for the formation and evolution of galaxies and structures is the hierarchical clustering or cold dark matter (CDM) model. It has demonstrated successes in reproducing the angular spectrum of the cosmic microwave background (CMB) radiation as well as many of the aspects of the distribution of large scale structure (see, e.g., Bahcall et al. 1999 and the references therein). However, at the individual galaxy level, the CDM model has encountered serious challenges in attempting to reproduce the observed galaxy properties. The standard CDM is now replaced by the  $\Lambda$ CDM paradigm, though many of the problems still remain.

In a recent article, Peeble (2002a) compared the current state of cosmology with the state of physics at the turn of the 19th/20th century, and commented that several known problems of the CDM could potentially turn out to be the same type of “Kelvin-level clouds” which a century ago resulted in the revolution of modern physics, i.e. the creation of relativity and quantum mechanics theories. These problems include “the prediction that elliptical galaxies form by mergers at modest redshifts, which seems to be at odds with the observation of massive quasars at  $z \sim 6$ ; the prediction of appreciable debris in the voids defined by  $L_*$  galaxies, which seems to be at odds with the observation that dwarf, irregular, and  $L_*$  galaxies share quite similar distributions; and the prediction of cusp-like dark matter cores in low surface brightness galaxies, which is at odds with what is observed” (Peebles 2002a).

Historically, CDM type of theories were invented partly to get around the problem that there does not seem to be sufficient time for the seeds of the anisotropies observed on the cosmic microwave background, about one part in  $10^5$ , to grow into the non-linear structures we see today by gravitational means alone, which requires seeds of one part in  $\sim 10^3$  at the time of recombination ( $z=1000$ ). Furthermore, the Big Bang nucleosynthesis model also requires a significant amount of non-baryonic dark matter (Primack 1999) if the universe is flat as the inflation scenario suggests.

Given the partially *ad hoc* nature of the introduction of the CDM (especially since after 30 years of search, no evidence of the existence of the CDM material has been found), it should not come as a total surprise that prob-

lems surface when observational data become available to allow a detailed comparison with the predictions of CDM model. In fact, most of the problems of the CDM scenario (which Peebles had quoted three above, and which we will list several more in the following) can be characterized by that it prescribes a medium for structure formation which is too clumpy (or can easily become too clumpy) on small scales, yet too smooth on large scales. For example, the cusp problem and the satellite abundance problem are all both due to the over-clumpiness of the medium on small scales, so is the problem of small disks or rapid angular momentum loss during disk formation (White & Frenk 1991); on the other hand, the over-smoothness of the medium on large scales underlies the problem of its inability to account for early quasar formation, the early formation of giant high redshift clusters (Francis et al. 1997; Steidel et al. 1998; Williger et al. 2002), as well as the problem of accounting for the observed bubble and void appearance of large-scale structure (Geller and Huchra 1984). Furthermore, in a purely bottom-up structure formation scenario such as the CDM, it is very difficult to account for the alignment of the spin axis of the bright galaxies in a cluster (Ozernoy 1994a and the references therein; Kim 2001), as well as the observed galaxy-cluster-supercluster alignment effect on large scale (West 2001).

In what follows we contrast a number of the major predictions of the hierarchical clustering (CDM)/merger scenario with that of the secular evolution (SE), focusing on individual galaxy properties, and compare both predictions with the known observational facts when available. Through this cross comparison, we wish to demonstrate that secular evolution is indeed a much more natural paradigm in explaining the properties (as well the evolution of these properties) of the observed galaxies:

- The CDM model predicts that the total number of galaxies of all Hubble types per comoving volume should decrease with time due to merger events; whereas SE predicts that the comoving number density of all Hubble types should remain nearly constant, and the number counts for individual Hubble types should evolve according to the morphological transformation picture. Recent large surveys such as the Caltech Faint Galaxy Redshift Survey (CFGRS) and Slone Digital Sky Survey (SDSS) have shown that there is essentially no evolution of the total number density of galaxies per co-moving volume between  $z=0$  and 1 (Cohen 2002; Yasuda et al. 2001).
- According to the CDM paradigm the field galaxies should evolve faster through merger process (since merger is known to happen more frequently in the fields), and rarely happens in clusters due to the relatively high speed nature of cluster galaxy encounters. SE on the other hand predicts that cluster galaxies should show a faster secular evo-

lution rate than field galaxies due to the tidal-interaction-enhanced and spiral-mediated mass redistribution. The well-known Butcher Oemler effect for cluster galaxies (Butcher & Oemler 1978a,b) as well as the observation of field galaxies (Ellis 1997) indicate that the cluster galaxies have a much large morphological evolution rate than field galaxies.

- In the CDM paradigm, there is no direct relation between the kinematics and energetics of the stars and gas in a given spiral disk; whereas the SE theory predicts that stars and gas should appear on the same energetic hierarchy at the 1 kpc spatial scale (Zhang 2002), because the interstellar medium receives similar amount of energy injection per unit mass from the spiral density wave as the stellar component. The observations indicate a clear correlation of stellar and gaseous kinematics on 1 kpc spatial scale (Larson 1979, 1981; Fleck 1982).
- The CDM galaxy formation model (Kauffmann 1996) prescribes that the collapse of gaseous material within the clustering dark matter halo produces disks, mergers of nearly equal mass disks produce ellipticals, and ellipticals subsequently grow disks if left undisturbed. One consequence of this prescription is that late-type spirals, which have a large disk-to-bulge ratio, should have older bulges than do early-type spirals, since to have a larger disk the galaxy must have been undisturbed and be able to accrete gas for a longer time, contrary to the observed trend (Wyse et al. 1997); the SE theory on the other hand predicts that the early type bulges are older since they have accreted mass for a longer time and most of the accreted mass is in stellar form from the local vicinity, since the central region formed stars early due to the deeper potential well and shorter dynamical time.
- The CDM theory does not predict any correlation of the disk heating time scale and the angular momentum transport time scale; whereas in the SE scenario these two time scales are found to be tightly correlated (see equations 2 and 4). The observed continuous change of bulge to disk ratio and other type of bulge-disk connections (Courteau et al. 1996) attest to the correlation of heating and angular momentum transport time scales during the morphological evolution of the disks.
- The disk galaxies produced in the CDM simulations are much too small and rotate much too fast compared to the observed galaxy disks (White & Frenk 1991; Navarro & Steinmetz 2000). This problem is made especially acute by the observational fact that the observed damped  $L_\alpha$  systems at high  $z$  (Wolfe 2001), which are the most likely candidates for primordial disks, are usually quite

large. SE starts from the initial condition of large disks at high  $z$ , which become the progenitors of today's large early type galaxies.

- The halo merging scenario tends to create a cuspy mass distribution in the center of a proto galaxy. The observed young galaxy candidates in the nearby universe, i.e., the low surface brightness (LSB) galaxies (Impey & Bothun 1997) and dwarf galaxies are found not to possess such cuspy cores (de Blok, McGaugh, & Rubin 2001). Even invoking maximum feedback does not solve the cusp problem (Gnedin & Zhao 2002). The SE scenario on the other hand starts from the more flattened morphological distribution of a LSB disk, and the central density of a galaxy is increased gradually through a Hubble time of evolution.
- The CDM simulations of galaxy formation have not been able to fit simultaneously the observed zero point of the Tully-Fisher (TF) relation and the local luminosity function, a problem related to the small-disk problem mentioned above (White & Frenk 1991). Furthermore, the CDM model naturally predicts that the luminosity of an individual galaxy is proportional to the third power of its circular velocity (White 1997; Dalcanton, Spergel & Summers 1997); To arrive at the observed fourth power TF relation requires fine-tuning of the feedback and cooling parameters (van den Bosch 2000). The SE scenario on the other hand predicts that the entire Hubble sequence from the spiral disks to disk ellipticals should follow roughly the same Tully-Fisher/Faber Jackson relation (Zhang 1999). No modified Newtonian dynamics is needed to explain the fact that LSB disks fall onto the same TF relation as normal spirals, as long as the decrease in surface brightness of a LSB galaxy is compensated by the increase of mass-to-light ratio in the usual virial theorem type of derivation of TF relation.
- In the CDM paradigm, large galaxies are formed out of the mergers of smaller ones, and therefore should form last. Recent studies of high  $z$  galaxies have shown that exactly the opposite is observed: i.e., the larger the mass of a galaxy, the shorter the time scale of its formation (Thomas, Maraston & Bender 2002; Boissier et al. 2001). In the SE scenario large galaxies tend to form quicker because of the more rapid gravitational collapse to form disks and the faster rate of evolution due to a more prominent spiral structure on the massive disk.
- The observed elliptical galaxies come in two types. While the boxy giant ellipticals have characteristics which indicate that they are likely to be the product of mergers, i.e., being pressure supported, having multiple nuclei, having two populations of globular clusters of different colors, and are radio and X-ray loud, etc., the more numerous disk

type ellipticals on the other hand are mostly rotationally supported, show little evidence of mergers, having only one globular cluster population, and being radio and X-ray quiet (Zhang 1999 and the references therein; Lee 2002). It is our belief that this dichotomy of characteristics is due to that boxy ellipticals are the true merger products, whereas disk ellipticals are produced mostly by secular evolution,

- N-body simulations have shown that stellar mergers tend to flatten out the abundance gradient from that of the observed power law shape (Mihos & Hernquist 1994a). Gas rich mergers (i.e., 10% gas) tend to create a distinctive dense core (Mihos & Hernquist 1994b) which is once again not observed in normal ellipticals. The multi-component merger scenario (Weil & Hernquist 1994, 1996) is not relevant to the explanation of the gradual decrease of disk galaxy population with decreasing redshift. The observed density and abundance profiles can be naturally produced and enhanced through secular evolution process.

The above comparison, as well as the fact (see, e.g. Peebles 2002b and the references therein) that it appears difficult to reproduce simultaneously the spectrum of  $L_\alpha$  forest (which requires plenty of small-scale CDM power) and the individual galaxy properties (which are troubled by too much small scale power) indicate that the true underlying structure formation theory may not be purely gravitational, but in addition may include other nonlinear processes such as primordial turbulence (von Weisacker 1951; Gamov 1952; Ozernoy 1974b). The supersonic shocks associated with turbulence can solve the time-of-growth problem of the high- $z$  quasars and high  $z$  ellipticals without the need of dark matter (though it does not necessarily exclude it); it also naturally produces the bubble and void appearance of the large scale distribution. Turbulence cascade can produce the observed scale-invariant mass spectrum (Ozernoy 1974b) just as the CDM theories. It also allow small scale structure to be present but not condense and collapse to form cusps and cores. The problem with the primordial turbulence scenario is of course why such supersonic motion has not left significant imprints on the cosmic microwave background: the observed CMB fluctuation of  $10^{-5}$  does not leave room for significant velocity fluctuation at the recombination time if the turbulent matter was coupled to radiation then. Recently, the first evidence of primordial turbulence in the form of a Kolmogorov scaling relation between temperature increment and angular separation on the CMB has been detected (Bershadskii & Screenivasan 2002). The issue of whether this indicates a real turbulent state of the matter at decoupling, or else it is rather the fossil of an earlier turbulent stage before decoupling (Gibson 2000) is not yet clear.

## IV. FUTURE RESEARCH

Even though the analytically derived evolution rates (2) (4) indicate that bulge formation through secular evolution is realistic if one adopts a realistic set of spiral parameters for pitch angle and wave amplitude, the past 2D N-body simulations have often produced much smaller spiral amplitude compared to those actually observed in physical galaxies and thus a relatively low evolution rate, especially when the adopted (bulge+halo) mass to disk mass ratio is high (a comparison of the 2D N-body simulation results of Zhang 1996 and Zhang 1999 shows clearly the effect of the spheroidal-to-disk ratio to the evolution rates obtained). This result is believed to be partly an artifact due to the enforcement of a rigid spheroidal component in the 2D simulations. Recent studies by Athanassoula (2002) found that making the halo active leads to enhanced bar formation. It is thus expected that an enhanced spiral formation and enhanced secular evolution rate will also be obtained in a full 3D and live halo simulation of spiral disks. Placing a galaxy under the tidal influence of neighboring galaxies in realistic group or cluster environment will also help to obtain a larger spiral amplitude and thus a higher evolution rate. Another issue which can be explored by a 3D simulation is the secular evolution caused by a skewed mass distribution such as found in the high- $z$  field galaxies in the Hubble Deep Fields. These skewed 3D mass distribution should produce the same kind of phase-shift and torque relations as in spiral galaxies. The secular evolution produced by these structures may also played a role for the direct formation of some high- $z$  elliptical galaxies (Peebles 2002c and the references therein) without going through the disk formation phase.

The secular evolution theory we presented here describes a morphological transformation process of individual galaxies. By itself it does not uniquely specify a cosmology, though it does hint at the elements and consequences of such a cosmology. For example, it favors large disks to form early, and subsequently undergo morphological transformation mainly due to the mediation of global structures such as spirals, bars, and three dimensional twisted isophotes. Environmental effect accelerates the evolution speed, but it operates mainly through the mediation of internal global structure, and not through the actual merging of galaxies. As we gradually eliminate uncertain elements from our knowledge of the galaxy formation process we will be able to better constrain the elements of earlier cosmological processes.

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